Original Research Article

Spatial and temporal characteristics of China's water footprint of energy and its matching relationship with water resources

Wei Guan[1,2*], Xiangning Zhao[1], Shuting Xu[2]

[1] *Center for Studies of Marine Economy and Sustainable Development, Liaoning Normal University, Dalian 116029, China. E-mail: lsgw2000@sina.com*

[2] *School of Geographical Sciences, Liaoning Normal University, Dalian 116029, China.*

ABSTRACT

Energy and water resources are very important for human survival and social development. Energy and water footprint can reflect the real occupation of water resources in the process of energy production. Based on the energy and water footprint evaluation model, this paper calculates the life cycle water footprint of fossil energy and power production in 30 provinces (cities and autonomous regions) in China, studies the temporal and spatial pattern evolution characteristics of China's raw coal, crude oil, natural gas, hydropower and thermal power from 2004 to 2016, and analyzes the spatial matching relationship between China's energy and water footprint and water resources. The results show that: (1): during the study period, the water footprint of fossil energy increases first and then decreases with 2012 as the boundary. The rapid growth of hydropower water footprint promotes the continuous growth of power water footprint. (2): In terms of spatial pattern, the water footprint of fossil energy increases in the West and decreases in the East with the Huhuanyong line as the boundary, and the Inner Mongolia, Shanxi and Shaanxi region as the high-value concentration area; in the power water footprint, there is a significant spatial boundary between hydropower water footprint and thermal power water footprint. The rapid growth of hydropower water footprint has gradually formed a high-value concentration area of power water footprint in the Yangtze River Basin, the Pearl River Basin and the southeast coast. (3): The spatial matching degree of energy and water footprint and water resources fluctuates and declines in the pattern of high in the south and low in the north. The spatial matching degree of fossil energy and water footprint is lower than that of electric power and water resources. The energy water contradiction between raw coal production and thermal power generation is the most prominent. One third of the country has the problem of energy water mismatch. North China with high energy and water footprint has great pressure on energy water matching. The contradiction between energy production and water resources allocation still exists. Truly reflect the matching relationship between energy and water footprint and water resources, help to optimize the comprehensive management of energy and water resources, and provide a quantitative basis for maximizing the energy water synergy.

Keywords: Energy Water Correlation; Energy and Water Footprint; Life Cycle Assessment; Water Resources; Spatial Matching; Green Development

1. Introduction

Energy and water resources are interdependent and mutually restricted. The continuous promotion of urbanization and industrialization in China not only promotes the sustainable growth of energy consumption, but also increases the consumption and pollution of water resources in energy production, processing and transportation. The contradiction between energy and water resources affects the sustainable development of social economy. As an important

indicator of water resource occupation and pollution in the process of energy production and consumption, energy and water footprint can effectively reflect the energy–water relationship.

Most of the relevant studies on energy and water footprint are concentrated after 2010, mainly on the calculation methods of energy and water footprint, and less on its spatial-temporal evolution and influencing factors[1-3]. The measurement of energy and water footprint can be divided into top-down and bottom-up methods. Most of the existing research methods for measuring energy and water footprints are top-down methods. The energy and water footprints of various economic sectors are calculated by energy consumption in monetary units, mainly using input-output methods[4-7]. For example, Okadera *et al.*[4] used the input-output method to analyze the water footprint of energy consumption in Liaoning Province of China from the perspective of energy consumption, and studied its external energy dependence; Zhang *et al.*[5] used MRIO model to analyze China's energy life cycle water use, water consumption and wastewater discharge from the perspective of consumption. The research time of the input-output method is limited by the preparation years of the national input-output table, so it is impossible to obtain the data in recent years. Compared with such methods, the bottom-up method can better reflect the current situation of energy and water footprint because the data in recent years are easier to obtain. The bottom-up method is to calculate the energy and water footprint through the physical quantity of various types of energy in the process of production and processing[8-11]. For example, Okadera *et al.*[8] calculated the energy and water footprint of Thailand from the perspective of energy production and supply; Scherer *et al.*[9] evaluated the water footprint of different types of hydropower departments; Dingning *et al.*[12] established an energy and Water Footprint Evaluation Model Based on ISO standard water footprint method from the perspective of improving water resource efficiency, and calculated the water footprint of China's primary energy and power production life cycle at the national and provincial levels. In this paper, the energy and water footprint evaluation

model[12] based on the life cycle of energy production from bottom to top is used to calculate the energy and water footprint, and the water footprint of fossil energy and electric power are compared and analyzed, in which the water footprint of fossil energy refers to the water footprint of primary fossil energy.

The existing energy and water footprint studies are mostly based on the cross-sectional data of a certain year, and lack of research on the time and space dimensions of energy and water footprint; secondly, some scholars analyzed the impact of energy and water footprint on the environment, but neglected the research on the spatial matching relationship between energy production and water resources; in addition, the research on the quantitative correlation between energy and water resources is of great significance to the cross basin energy water security. Based on this, this paper studies the temporal and spatial characteristics of China's energy and water footprint from 2004 to 2016, and analyzes the spatial matching degree between China's energy and water footprint and water resources, in order to provide a new perspective for the study of energy water relationship and a quantitative basis for the regional energy transformation and development of coordinated energy and water resources.

2. Research methods and data sources

2.1 Energy and water footprint evaluation model

The energy and water footprint evaluation model is established based on the ISO standard water footprint method[13]. Starting from the life cycle of energy production, it covers mining, treatment, processing and transformation, use, waste treatment, etc., in the life cycle. The energy and water footprint evaluation model is used to calculate the water footprint in the production life cycle of fossil energy (raw coal, crude oil, natural gas) and electric power (hydropower and thermal power). Hydropower and thermal power are referred to as hydropower and thermal power in this paper. The energy and water footprint includes the

direct water footprint in the production life cycle and the indirect water footprint brought by the materials and energy input in the production process. Since it is difficult to obtain the data of water pollution in the life cycle of energy production, the water pollution caused by energy production is represented by the grey water footprint[14,15] in the WFN water footprint method. The energy water footprint is divided into energy blue water footprint and energy grey water footprint. The energy blue water footprint is the surface runoff and groundwater from rivers, lakes and aquifers required in the production process, and the energy grey water footprint is the amount of water required to dilute the polluted water in the production process to the discharge standard. The formula of energy and water footprint evaluation model is:

$$EPWF = PWF_{direct} + PWF_{indirect} =$$
$$PWF_{b,d} + PWF_{g,d} + PWF_{b,in} + PWF_{g,in} \tag{1}$$

Where: $EPWF$ refers to the water footprint of unit energy output; PWF_{direct} refers to the direct unit output water footprint of the energy production process; $PWF_{indirect}$ refers to the indirect unit output water footprint of the energy production process; $PWF_{b,d}$ refers to the blue water footprint of direct unit output in the energy production process; $PWF_{g,d}$ refers to the direct unit output grey water footprint of the energy production process; $PWF_{b,in}$ refers to the blue water footprint of indirect unit output of energy investment; $PWF_{g,in}$ refers to the grey water footprint of indirect unit output of energy investment. Considering all the processes in the life cycle, the water footprint of the energy system shall be the sum of the water footprints in each life cycle stage, expressed by the following formula:

$$EPWF = \sum_{m=1}^{n} \left(PWF_{m(b,d)} + PWF_{m(g,d)} \right) +$$
$$\sum_{n=1}^{n} \left(PWF_{n(b,in)} + PWF_{n(g,in)} \right) \tag{2}$$

Where: m refers to the m-th production process; n refers to class n energy; the meanings of other variables are the same as above. The calculation formula of grey water footprint of each energy unit

output is as follows:

$$PWF_{g,d} = \frac{L \times V}{C_{max} - C_{nat}} = \frac{G}{C_{max} - C_{nat}} \tag{3}$$

Where: L refers to the unit energy production wastewater discharge (M³/GJ) V refers to the amount of pollutants in the discharged wastewater (mg/m³) G = LV refers to the unit energy production pollutant discharge (mg/GJ) C_{max} refers to the acceptable pollutant concentration in water (mg/m³), C_{nat} refers to the pollutant concentration in natural water(mg/m³).

The calculation formula of energy and water footprint EWF is as follows:

$$EWF = \sum_{n=1}^{n} EWF_n = \sum_{n=1}^{n} \left(EPWF_n \times P_n \right) \tag{4}$$

Where: EWF_n refers to the energy and water footprint of class n; $EPWF_n$ refers to the water footprint per unit output of class n-th energy; P_n refers to the energy output of category n.

2.2 Center of gravity and standard deviation ellipse model

The coincidence area of center of gravity distance and standard deviation ellipse is used to analyze the overall matching degree of energy and water footprint and water resources in space. The coverage area of the standard deviation ellipse reflects the main area of the energy and water footprint and the spatial distribution of water resources. The distance between the centers of gravity of the two reflects the difference and overall matching degree of the energy and water footprint and the spatial distribution of water resources. The greater the distance between the centers of gravity, the smaller the matching degree, and vice versa. The calculation formula is:

$$x = \sum_{i=1}^{n} G_{ij} x_i \bigg/ \sum_{i=1}^{n} G_{ij} , y = \sum_{i=1}^{n} G_{ij} y_i \bigg/ \sum_{i=1}^{n} G_{ij} \tag{5}$$

Where: (x, y) is the center of gravity coordinate of energy and water footprint and the center of gravity coordinate of available water resources; n is the number of areas, $n = 30$; (x_i, y_i) is the barycentric coordinate of the spatial weight of the i region; G_{ij} is the spatial weight of the ith region

in the jth year.

2.3 Energy and water footprint pressure index

In order to compare and analyze the matching degree of energy and water footprint and water resources in different regions, the energy and water footprint pressure index F is constructed with reference to relevant research[16-18] to represent the pressure of water footprint on water resources in the life cycle of energy production. The larger the energy and water footprint pressure index, the smaller the matching degree between energy and water footprint and available water resources. The specific formula is as follows:

$$F_{ij} = \frac{EWF_{ij}}{Q_{ij}}$$

(6)

Table 1. Water footprint value per unit of production in energy production life cycle in China

Energy type	Classification	Energy production and processing process	Classification of water footprint per unit energy output	Water footprint per unit energy output /(m³/GJ)	Ref.
Fossil energy	Coal	Raw coal mining	Direct blue water footprint of raw coal	0.014	[21]
			Direct grey water footprint of raw coal	0.137	[22]
		Coal washing	Coal washing direct blue water footprint	0.007	[21]
			Direct grey water footprint of coal washing	0.027	[22]
	Petroleum	Crude oil exploitation	Direct blue water footprint of crude oil	0.167	[23]
			Direct grey water footprint of crude oil	0.016	[24,25]
		Machining	Direct blue water footprint of crude oil processing	0.057	[26]
			Direct grey water footprint of crude oil processing	-	
	Natural gas	Exploitation	Natural gas direct blue water footprint	0.077	[27]
			Natural gas direct grey water footprint	0.013	[25,28]
		Processing purification	Direct blue water footprint of natural gas processing	0.006	[29]
			Direct grey water footprint of natural gas processing	-	
Power	Hydropower	Evaporation and leakage of reservoir	Hydropower direct blue water footprint	6.750	[30]
		Construction of hydropower plant	Indirect blue water footprint of hydropower	0.002	[12]
	Thermal power	Cooling system	Thermal power direct blue water footprint	0.681	[31]
			Thermal power direct grey water footprint	0.083	[19,28,32]
		Energy input of thermal power	Thermal power indirect blue water footprint	0.063	[19]
			Indirect grey water footprint of thermal power	0.387	[19]

Where: F_{ij} is the energy water footprint pressure index of i region in the year of j, and EWF_{ij} is energy water footprint of i region in the year of j, Q_{ij} refers to available water resources of i region in the year of j.

2.4 Data source

This paper selects the data from 2004 to 2016 to analyze the temporal and spatial characteristics of energy and water footprint and its matching relationship with water resources in 30 provincial administrative regions of China (Tibet, Hong Kong, Macao and Taiwan are not included due to lack of data). The energy production comes from the *China Energy Statistical Yearbook*[19], and the average low calorific value coefficient of each energy comes from the 2017 *China Energy Statistical Yearbook*[19]. The water footprint values and data sources per unit

output in the life cycle of various types of energy production are shown in **Table 1**. When calculating the grey water footprint of each energy unit output, COD, the chemical oxygen demand of main pollutant in wastewater discharge, is used as the measurement index for calculating the grey water footprint of energy. Due to the complexity of energy consumption calculation in the process of fossil energy production, only the direct water footprint of fossil energy is calculated. The study shows the current situation of water resources in each region by the available water resources. The available water resources are calculated according to 40% of the total water resources[18], and the total water resources come from the *China Statistical Yearbook*[20].

The COD content of wastewater from raw coal mining and coal washing is 200 g/t and 30 g/t, respectively[21]. The maximum acceptable COD value in wastewater discharge of coal industry is 70 mg/L[21]. The consumption of water resources during crude oil exploitation is defined as 7 m^3/t[23]. Water consumption during oil processing is defined as 2.37 m^3/t[26]. The water quota of drilling mud during natural gas production is 30 m^3/10,000 m^3[27]. During natural gas processing, the unit production water consumption of the purification unit is 2.4 m^3/10,000 m^3[29]. The data of COD emission during the exploitation of crude oil and natural gas comes from the *China Environmental Statistics Yearbook*[25]. The COD emission from crude oil exploitation is 821 mg/GJ and that from natural gas exploitation is 379 mg/GJ. According to the pollutant discharge standard for petroleum refining industry[24], the maximum acceptable COD value in the wastewater discharge of petroleum industry is 50 mg/L. The direct grey water footprint of petroleum processing process is not calculated in this paper due to the lack of data. Since there is no specific pollutant discharge standard for the natural gas industry, the study refers to the environmental quality standard for surface water[28], and 30 m/L is selected as the maximum acceptable COD value in the wastewater discharge of the natural gas industry.

The water consumption during hydropower generation mainly comes from the evaporation and leakage of the reservoir, that is, the direct blue water footprint[30]. The indirect blue water footprint of hydropower refers to the water consumption of dam construction, which is 0.00168 m^3/GJ[12]. In the selection of parameters for direct grey water footprint of thermal power, the production and emission coefficient[32] is used to calculate the amount of COD produced by the unit product of thermal power generation. The proportion of energy and fuel input in the thermal power industry is derived from the national energy balance table in the 2017 *China Energy Statistical Yearbook*. With reference to the environmental quality standard for surface water[28], 30 m/L is selected as the maximum acceptable COD value in the wastewater discharge of thermal power industry. The indirect blue water footprint of thermal power is the blue water footprint of energy input in the process of thermal power, and the indirect grey water footprint of thermal power is the grey water footprint of energy input in the process of thermal power.

3. Results and analysis

3.1 Analysis of space-time characteristics of energy and water footprint

3.1.1 Analysis of time evolution characteristics of energy and water footprint

Based on the energy and water footprint evaluation model, the energy and water footprint values of China's raw coal, crude oil, natural gas, hydropower and thermal power from 2004 to 2016 are calculated according to formulas (1)–(4), and the results are shown in **Figure 1**. During the study period, the water footprint of fossil energy first increased and then decreased in 2012. The rapid growth of market energy demand from 2004 to 2012 led to the continuous growth of fossil energy output at this stage, and the water footprint of fossil energy continued to grow to reach the highest value of 18.573 billion m^3 in 2012; 2012–2016 is in the "12th Five Year Plan" strategic period of energy. The energy structure has been continuously optimized and upgraded, the total output of fossil energy has decreased, and the water footprint of fossil energy has decreased. From the perspective of energy and water footprint structure, the original

coal water footprint of fossil energy water footprint accounts for about 84% and has been stable for a long time. The proportion of crude oil water footprint is 11%–18%, showing a continuous decreasing trend. The proportion of natural gas water footprint is the smallest, but showing a continuous increasing trend. From the perspective of fossil energy grey water footprint, the proportion of fossil energy grey water footprint in the fossil energy water footprint is as high as 70%. The temporal evolution characteristics of fossil energy grey water footprint are basically consistent with that of fossil energy water footprint, reaching the highest value of 14.457 billion m^3 in 2012.

The power and water footprint showed a sustained and rapid growth trend from 2004 to 2016. The electric power water footprint in 2016 was 48.279 billion m^3, three times that of 2004. This is due to the continuous growth of electric power production in the power industry due to the influence of national policies and other factors during this period. From the perspective of power water footprint structure, the proportion of hydropower water footprint increased from 52% in 2004 to 60% in 2016, and the proportion of thermal power water footprint gradually decreased. From the perspective of power grey water footprint, the time series evolution characteristics of power grey water footprint are basically the same as that of power water footprint, reaching a maximum of 7.507 billion m^3 by 2016. The proportion of power grey water footprint in power water footprint is less than 20% and is decreasing.
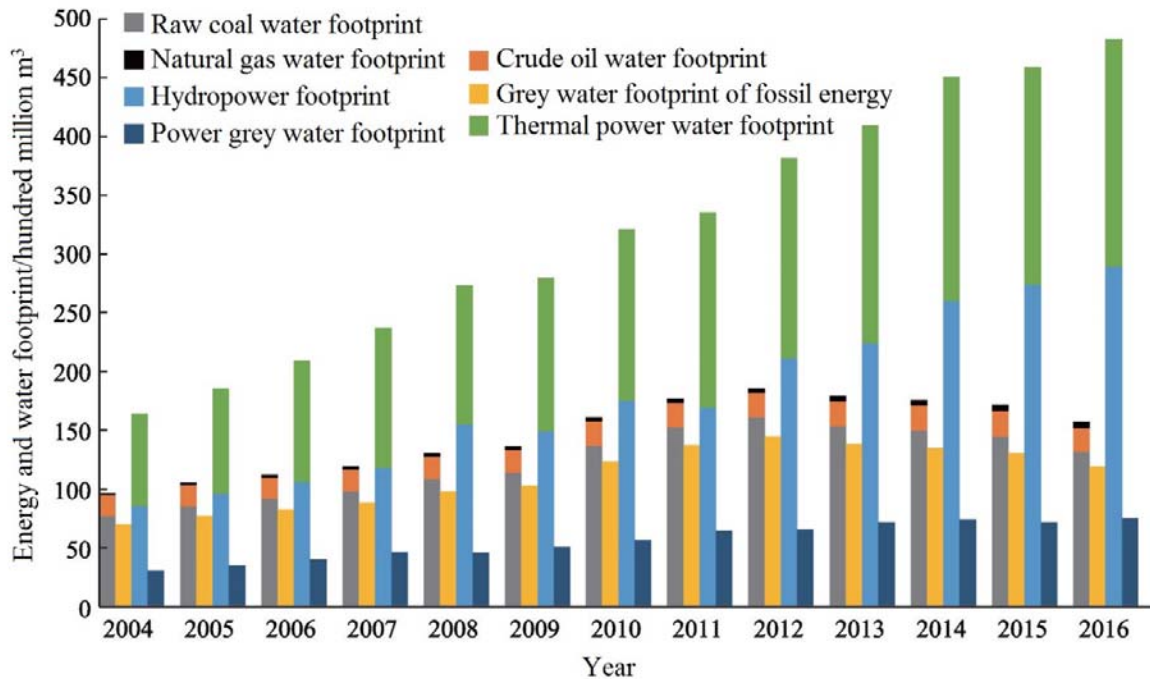

Figure 1. Water footprint of energy in China, 2004–2016.

Comparing the fossil energy and electric water footprints in **Figure 1**, it is found that the electric water footprint is larger than the fossil energy water footprint, and the gap between the two is gradually increasing. The ratio of fossil energy water footprint to electric water footprint gradually increased from 1:1.71 in 2004 to 1:3.07 in 2016. Among the five types of energy and water footprints, the growth rate of hydropower and water footprints is the fastest, with an average growth rate of 1.293 billion m^3/a. As a result, the rapid growth of power and water footprints has not led to a significant increase in power grey water footprints. By 2016, the power grey water footprints were only 63% of the fossil energy grey water footprints. This shows that under a certain amount of energy production, the increase in the proportion of hydropower in the energy production structure not only makes full use of water resources, but also directly reduces the pollution of energy production to water resources.

3.1.2 Analysis on spatial evolution characteristics of energy and water footprint

The spatial distribution of China's energy and water footprints is quite different, which is caused by different conditions such as resource endowment, economic development direction and policy support in various regions. In order to reveal the spatial evolution characteristics of China's energy and water footprint, based on the energy and water footprint values of 30 provinces (cities, autonomous regions) in China, ArcGIS 10. 2 software is used to map and analyze the spatial distribution and evolution characteristics of various energy and water footprints, as shown in **Figure 2** and **Figure 3**.
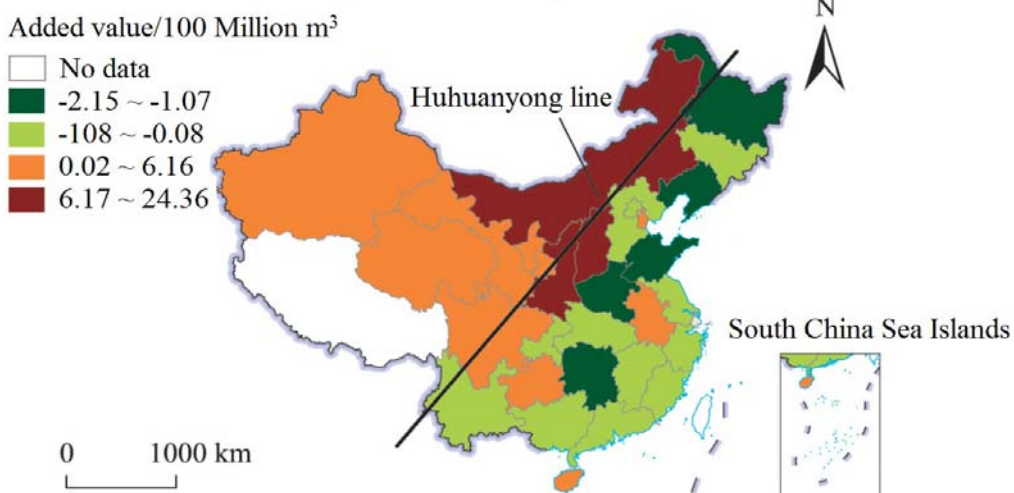
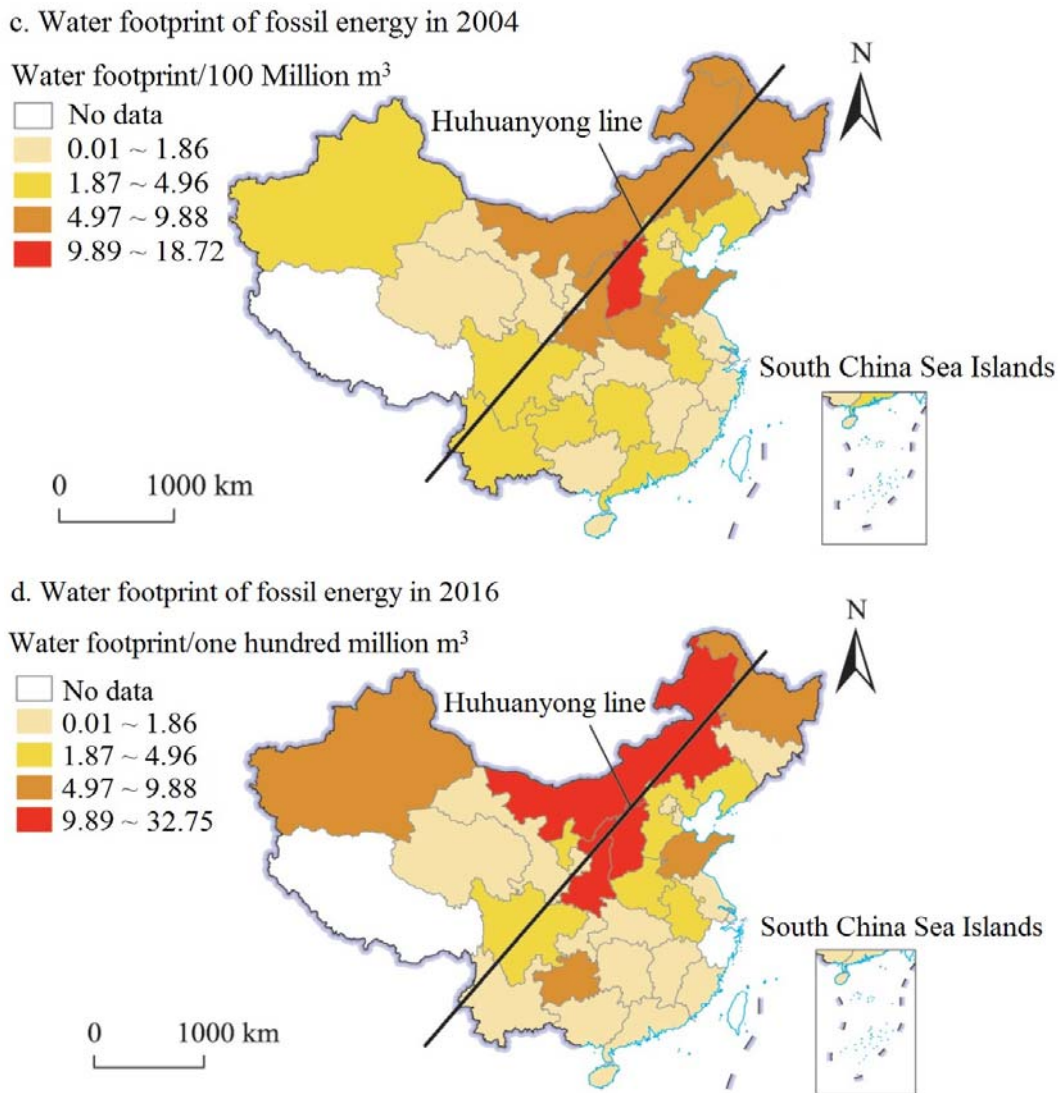As shown in **Figure 2a**, the distribution of water footprint of fossil energy is consistent with

the layout of main fossil energy producing areas. Raw coal and water footprints are widely distributed with high-density, forming major high-value agglomeration areas in Inner Mongolia, Shanxi, Shaanxi and Henan along Taihang Mountain and Helan Mountain, and relatively high-value agglomeration areas in Sichuan, Guizhou and Yunnan. Compared with the raw coal water footprint, the crude oil water footprint and natural gas water footprint are scattered, and no obvious high-value agglomeration area is formed. The high value areas of crude oil water footprint mainly include Northeast China, Bohai Rim region, Shaanxi, Guangdong and Xinjiang, and the high value areas of natural gas water footprint mainly include Sichuan, Xinjiang, Shaanxi, Qinghai, Heilongjiang and Guangdong. It can be seen from

a. Density of each fossil energy water footprint
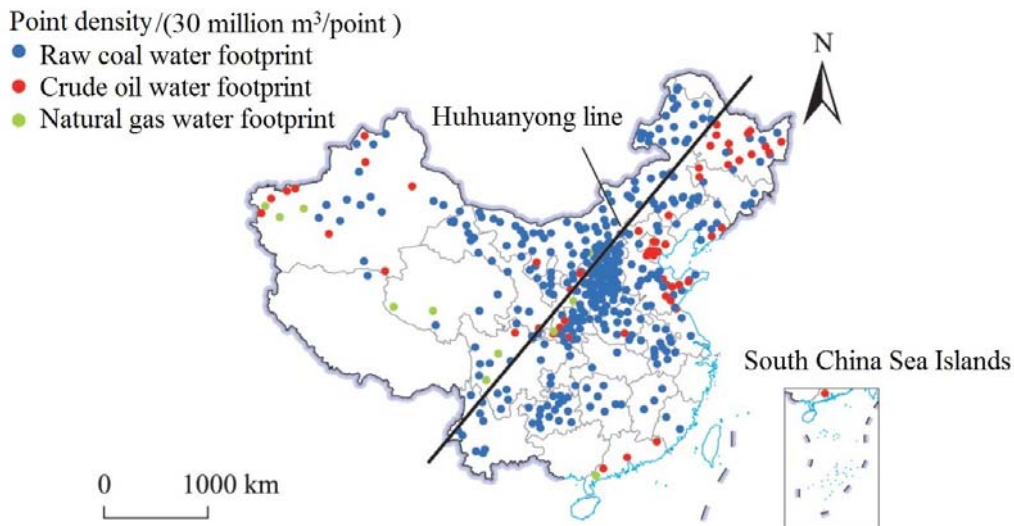
b. Added value of water footprint of fossil energy from 2004 to 2016

c. Water footprint of fossil energy in 2004

Water footprint/100 Million m³

☐	No data
	0.01 ~ 1.86
	1.87 ~ 4.96
	4.97 ~ 9.88
	9.89 ~ 18.72

Huhuanyong line

South China Sea Islands

N

0   1000 km

d. Water footprint of fossil energy in 2016

Water footprint/one hundred million m³

☐	No data
	0.01 ~ 1.86
	1.87 ~ 4.96
	4.97 ~ 9.88
	9.89 ~ 32.75

Huhuanyong line

South China Sea Islands

N

0   1000 km

Drawing review No.: GS (2019) No.1825.
Figure 2. Distribution and spatial variation of the water footprint of fossil energy in 30 Provinces of China, 2004–2016.
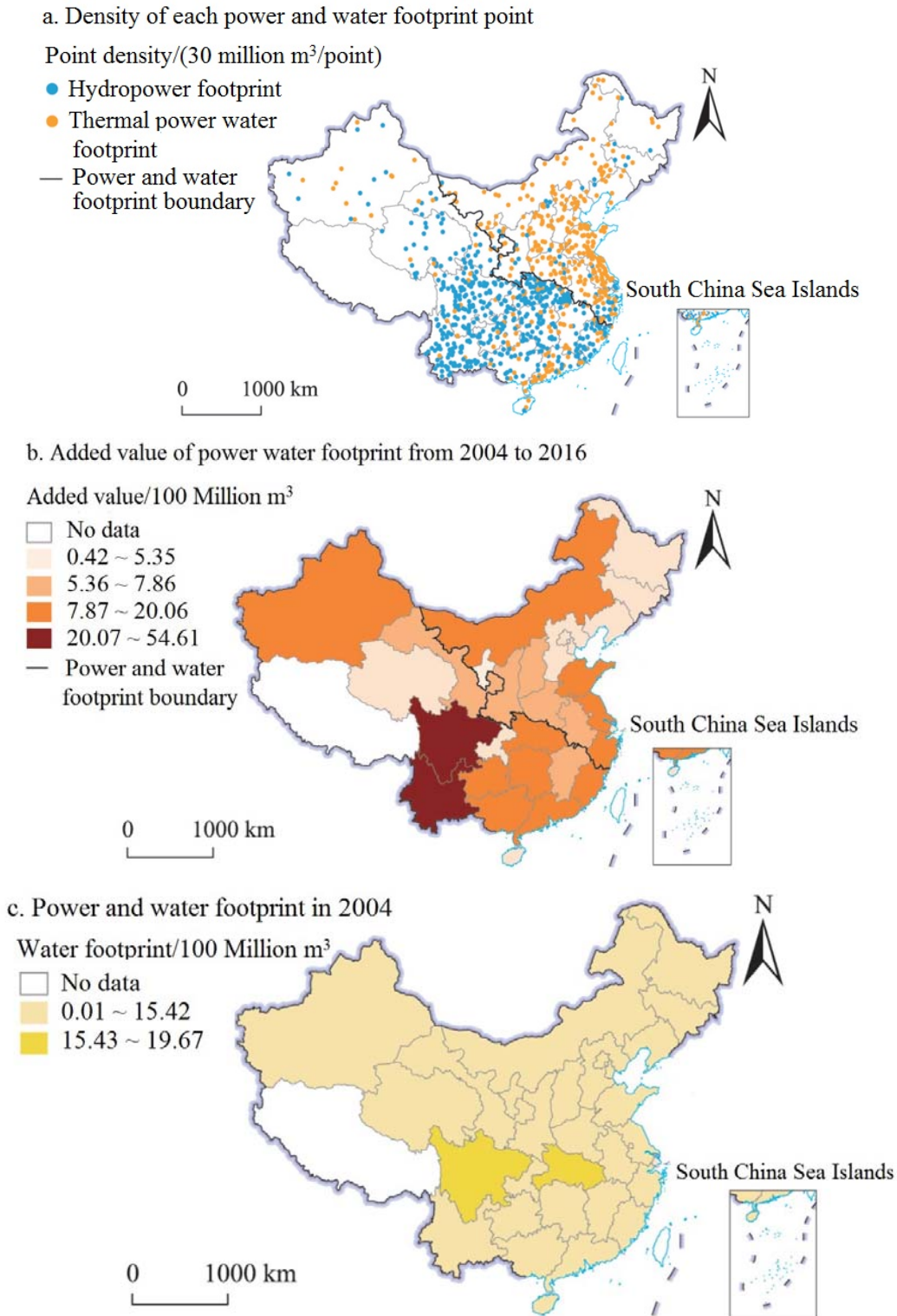
Figure 2b that the water footprint of fossil energy during the study period is mainly bounded by the Huhuanyong line, increasing in the West and decreasing in the East. Since most of China's major energy production areas, which are composed of five national comprehensive energy bases in Shanxi, Inner Mongolia, Ordos Basin, Xinjiang and southwest China, are located in the west of Huhuanyong line, with the increase of fossil energy production, the water footprint of fossil energy shows an increasing trend, with an increase of 0.02–24.36 billion m³. The increment of fossil energy in Shanxi, Inner Mongolia, Shaanxi and Northwest China is mainly raw coal. In particular, the output of raw coal in Shanxi and Inner Mongolia provinces (autonomous regions) has increased the most, and the increment of water footprint of fossil energy in

the two provinces (autonomous regions) is the highest. Only natural gas production in Sichuan has increased, and the increment of its fossil energy water footprint is much smaller than that in other regions. As the main energy consumption area in China, the area to the east of Huhuanyong line has significantly reduced the output of fossil energy in most areas, and the water footprint of fossil energy has decreased, with a decrease of 0.08–2.15 hundred million m³. It is found that the Huhuanyong line is not only the dividing line of China's population, but also an important dividing line of the spatial evolution of China's fossil energy water footprint. With the westward migration of the national energy supply strategy, it also has a great impact on the spatial pattern of China's fossil energy water footprint. Compared with **Figure 2c–d**,

86

it can be found that the evolution trend of high-value area changes form concentrating along the Huhuanyong line in 2004 to focusing on the Inner Mongolia Shanxi Shaanxi region 2016.
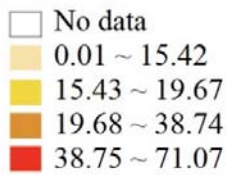
As shown in **Figure 3a**, the distribution of thermal power water footprint is highly related to the raw coal production area, while the distribution of hydropower water footprint is mainly affected by the abundance of water resources. Based on the proportion of thermal power water footprint and hydropower water footprint in the power water footprint, Inner Mongolia, Shanxi, Shaanxi, Henan, Shandong and other regions to the north of the power water footprint boundary are rich in coal resources, and the proportion of thermal power water footprint is higher than 50%, forming a

a. Density of each power and water footprint point

Point density/(30 million m³/point)
- Hydropower footprint
- Thermal power water footprint
— Power and water footprint boundary

b. Added value of power water footprint from 2004 to 2016

Added value/100 Million m³
- No data
- 0.42 ~ 5.35
- 5.36 ~ 7.86
- 7.87 ~ 20.06
- 20.07 ~ 54.61
— Power and water footprint boundary

c. Power and water footprint in 2004

Water footprint/100 Million m³
- No data
- 0.01 ~ 15.42
- 15.43 ~ 19.67

Figure 3. Distribution and spatial variation of the water footprint of power in 30 Provinces of China, 2004–2016.

thermal power water footprint agglomeration area; Sichuan, Hubei, Yunnan, Guizhou, Guangxi and other regions to the south of the power water footprint boundary are abundant in water resources. The proportion of hydropower water footprint is higher than 50%, forming a hydropower water footprint agglomeration area. As can be seen from **Figure 3b**, the power and water footprints of all provinces (cities and autonomous regions) in China showed an increasing trend year by year from 2004 to 2016, with an increase range of 0.42–54.61 billion m³. The power and water footprint increment in the south of the power and water footprint boundary is generally higher than that in the north of the boundary. This is because the Yangtze River Basin, the Pearl River Basin and the southeast coast to the south of the power water footprint boundary have abundant water flow and the terrain conditions suitable for the construction of hydropower stations. With the strong support of national policies, their hydropower projects have developed rapidly. In particular, after 2013, Jinping Hydropower station in Sichuan Province and Xiangjia hydropower station at the border of Sichuan Province and Yunnan Province have been put into operation, which has greatly increased the hydropower production of Sichuan and Yunnan, Maximize the power and water footprint increment. In the area north of the power water footprint boundary, Beijing, Tianjin, Hebei, Shanxi and Henan region is under strict control, and its

large and medium-sized cities and nearby areas will not be equipped with new coal-fired power plants, thus limiting the growth rate of its thermal power water footprint. Inner Mongolia and Xinjiang have more coal resources. In order to promote the rapid development of local economy, new thermal power projects have been added, resulting in more increment of thermal power water footprint. The rapid development of hydropower and the effective control of thermal power have gradually increased the spatial difference of China's power water footprint. Compared with **Figure 3c–d**, it can be found that from 2004 to 2016, the power water footprint gradually formed a spatial evolution trend of high-value concentration along the Yangtze River Basin, the Pearl River Basin and the southeast coast.

3.2 Spatial matching relationship between China's energy and water footprint and water resources

The geographical and spatial differences in China's water resources restrict the development of the energy industry. At the same time, the increase in energy production has also increased the pressure on water use in various regions to varying degrees. In some regions where water resources are scarce, the growth of energy and water footprint is easier to accelerate the shortage of local water resources and water pollution. In order to analyze the matching relationship between China's energy and water footprint and the spatial pattern of water resources,

ArcGIS 10.2 software is used to generate the ellipse of the center of gravity and standard deviation of the energy and water footprint and available water resources from 2004 to 2016. Formula (5) is used to calculate the center of gravity coordinates of the energy and water footprint and available water resources at five time nodes from 2004 to 2016, and then calculate the relative center of gravity distance, as shown in **Figure 4** and **Table 2**. For the convenience of observation, only the standard deviation ellipse of the start and end years is displayed.
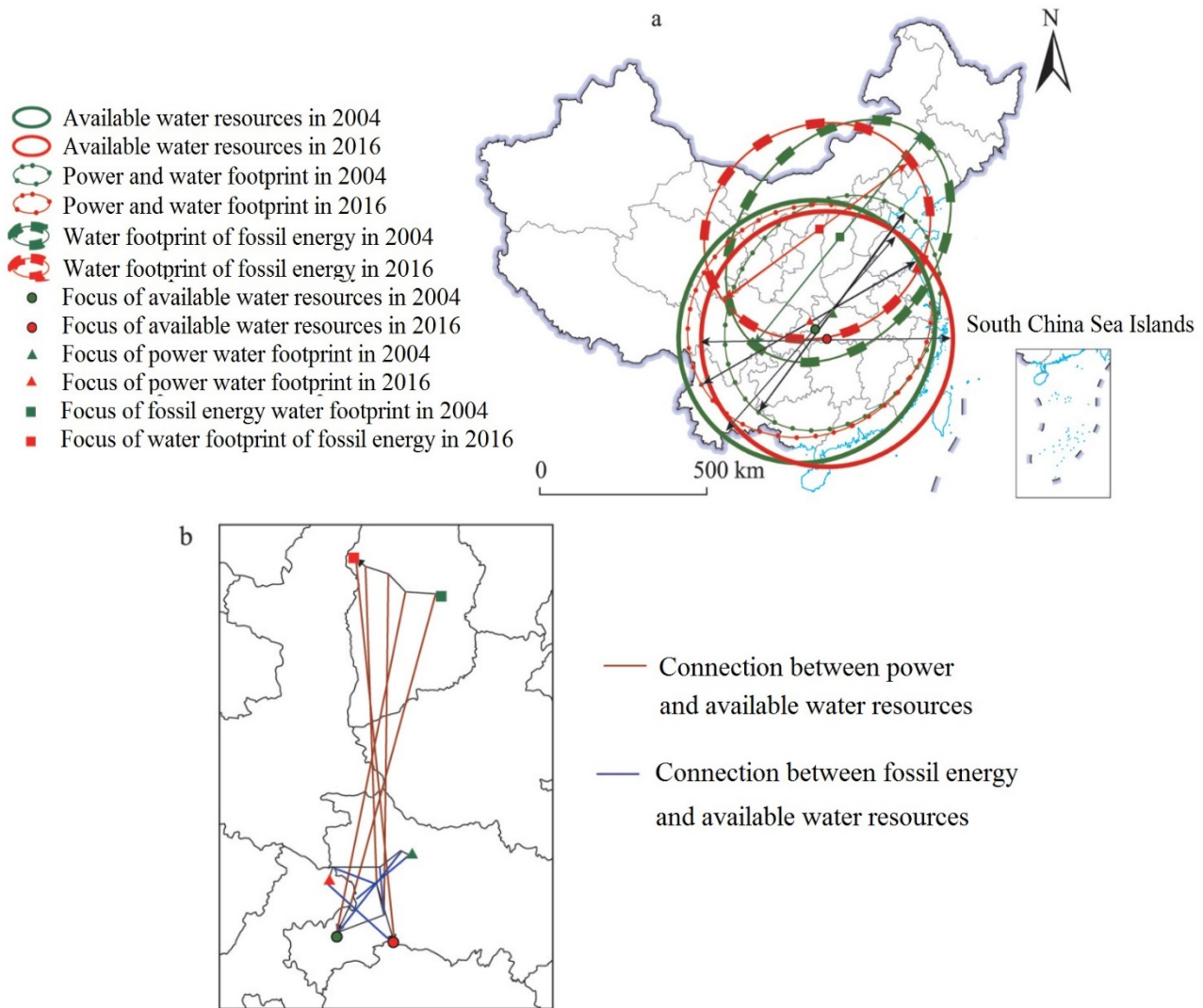
Drawing review No.: GS (2019) No.1825.

Figure 4. Gravity center and standard deviation elliptic distribution of the water footprint of energy and available water resources in China.

Table 2. Gravity center relative distance between the water footprint of energy and available water resources in China, 2004–2016

Classification	2004	2007	2010	2013	2016
Relative center of gravity distance between fossil energy water footprint and available water resources/km	728.177	789.021	773.555	721.311	876.097
Distance of relative gravity center between electric power water footprint and available water resources/km	189.075	256.811	123.271	98.302	208.090

It can be seen from **Figure 4a** that the standard deviation ellipse of available water resources and electric power water footprint covers most of central and southern China, and the standard deviation ellipse of fossil energy water footprint covers most of central and Northern China with high fossil energy output. The intersection area of the standard deviation ellipse of the electric power water footprint and the standard deviation ellipse of the available water resources is large, which indicates that the electric power water footprint and the available water resources are highly matched in

89

the spatial pattern. The intersection area between the standard deviation ellipse of fossil energy water footprint and the standard deviation ellipse of available water resources is relatively small, indicating that the matching degree between fossil energy water footprint and available water resources is lower than that between electric power water footprint and available water resources.

It can be seen from **Table 2** and **Figure 4b** that the distance between the center of gravity of the fossil energy water footprint and the available water resources is larger than that of the electric power water footprint. It has been further verified that the spatial matching degree between the fossil energy water footprint and the available water resources is low. From 2004 to 2016, the center of gravity of available water resources moved irregularly, the center of gravity of fossil energy water footprint moved to the northwest as a whole, and the center of gravity of electric power water footprint moved to the southwest as a whole. The distance between the center of gravity of fossil energy water footprint, electric power water footprint and available water resources showed a fluctuating growth trend. It shows that the matching degree of fossil energy water footprint, electric power water footprint and available water resources in spatial pattern has decreased. After 2013, the distance between the center of gravity of fossil energy water footprint, electric power water footprint and available water resources has increased significantly, that is, the commissioning of West–East power transmission, Xinjiang outward power transmission and other projects has a certain impact on local water resources in the geographical and spatial dimension.

3.3 China's energy and water footprint pressure index

There is a "barrel" principle in the matching degree between energy water footprint and available water resources, that is, it is jointly restricted by the pressure index of fossil energy water footprint and the pressure index of electric power water footprint. If either index is too high, it will put pressure on water resources. **Figure 5** shows the spatial matching degree of energy and water footprints and available water resources of

China's provinces (cities and autonomous regions) in 2016. According to the research, they are divided into three types according to the matching degree: (1) when $F > 40\%$, it is an energy–water relationship tense area, that is, energy production has caused great pressure on the local water resources environment, and even caused pollution and shortage of water resources, and the relationship between energy and water resources is tense; (2) when F is between 10%–40%, it is a restricted area of energy–water relationship, that is, energy production has a certain pressure on the local water resources environment, and the development of the local energy industry is restricted by water resources; (3) when $F < 10\%$, the energy water relationship is moderate, that is, the pressure of energy production on the local water resources environment is small, and the relationship between energy and water resources is relatively mild.

It can be seen from **Figure 2**, **Figure 3** and **Figure 5** that regions with high water footprint pressure index of fossil energy are mainly distributed in high-value coal water footprint concentration areas in Taihang Mountain and Helan Mountain, and regions with high power water footprint pressure index are mainly distributed in high-value thermal power water footprint concentration areas in the eastern region. On the whole, the matching degree of energy and water footprint and available water resources is high in the south and low in the north. In the north, the energy water relationship is tense and the energy water relationship is restricted, while in the south, the energy water relationship is moderate. The proportion of raw coal water footprint and thermal power water footprint of energy and water footprint in regions with energy water relationship tension and energy water relationship restriction is large. Most of the regions are both high value regions of raw coal water footprint and thermal power water footprint, and regions with high pressure of energy water matching, indicating that the spatial distribution pattern of raw coal water footprint and thermal power water footprint is the main factor negatively affecting the spatial matching of energy and water footprint and water resources. The energy
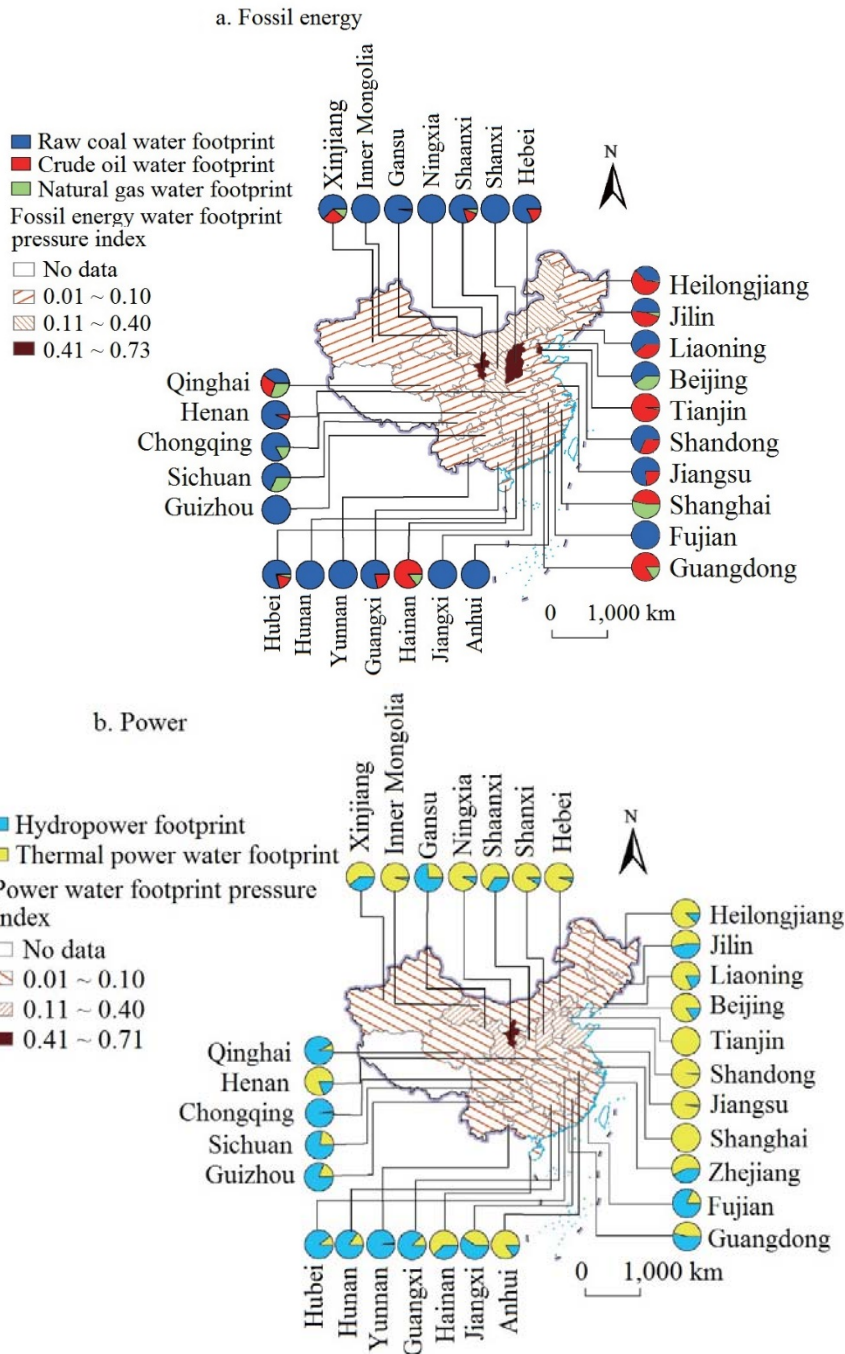
Figure 5. Spatial matching relation between the water footprint of energy and available water resources in 30 Provinces of China, 2016.

water contradiction between raw coal production and thermal power generation is the most prominent.

There are three provinces (cities and autonomous regions) with tight energy water relationship, namely, Ningxia, Tianjin and Shanxi. These regions are extremely deficient in water resources, and their available water resources rank first, second and fifth from the bottom of the country. The water footprint of fossil energy in Ningxia and Shanxi is dominated by that of raw coal, and the water footprint of electric power in the three regions is dominated by that of thermal power. Among them, although the water footprint of fossil energy and electric power in Ningxia is small, the serious scarcity of water resources in Ningxia has led to a tense relationship between local energy and water resources. Shanxi's raw coal water footprint and thermal power water footprint are both high, resulting in its fossil energy water footprint pressure index and electric power water footprint pressure index being much higher than that of other regions.

91

In addition, Tianjin is rich in oil resources. Its original oil-water footprint is high and accounts for a large proportion in the water footprint of fossil energy, resulting in a prominent contradiction between Tianjin's crude oil production and local water resources.

There are seven provinces (cities and autonomous regions) with restricted energy–water relationship, namely, Inner Mongolia, Gansu, Shaanxi, Hebei, Shandong, Beijing and Shanghai, all of which are relatively short of water resources, and the water footprint of fossil energy in these regions (except Shanghai) is mainly raw coal water footprint, and the water footprint of electric power in these regions (except Gansu) is mainly thermal power water footprint. Among them, the economic development of Shandong, Inner Mongolia and Shaanxi is dominated by the secondary industry, with large energy output and high energy and water footprints. Their energy production has caused certain pressure on local water resources. The Yangtze River Basin in Gansu Province is rich in water resources. A certain number of hydropower projects have been built, resulting in the proportion of hydropower water footprint in Gansu Province is greater than that of thermal power. However, the distribution of water resources in Gansu Province is extremely uneven and in general is relatively short, resulting in certain restrictions on its energy production. In addition, Beijing and Shanghai have a high degree of economic development and a large population density. Under the influence of industrial structure, national policies and other factors, their fossil energy production structure is relatively optimized. The proportion of natural gas water footprint is much higher than that of other regions. The overall energy and water footprint are low, but their available water resources are small, ranking the third and fourth from the bottom of the country, resulting in a large pressure index of power and water footprint in Beijing and Shanghai.

The number of regions with moderate energy water relationship accounts for 60%, including the southern region, the three northeastern provinces, Xinjiang and Qinghai. The southern region has less fossil energy reserves, more water resources reserves, and the overall water footprint of fossil

energy is low. In most regions, hydropower is the main mode of power production, and the proportion of hydropower and water footprint is high. Therefore, the local energy and water footprint is relatively matched with water resources. Xinjiang is a vast and sparsely populated region with uneven distribution of water resources. The overall water resources and energy reserves are large, and the types of fossil energy are rich. However, due to the backward economic development and the lower degree of energy development than other regions, the pressure index of its energy and water footprint is small. Although the three provinces in Northeast China are rich in coal resources, the poor geological conditions of raw coal mining restrict the development of coal and thermal power industries, making their energy and water footprints smaller than other regions rich in energy reserves, and the local energy production has less pressure on water resources.

4. Conclusion and discussion

4.1 Conclusion

This paper adopts the bottom-up energy and water footprint evaluation model, which overcomes the characteristics of the inability of the top-down input-output model to reflect the current situation of energy and water footprint due to data limitations. Through the empirical study on the time sequence and spatial pattern evolution of China's fossil energy water footprint and electric power water footprint, the change tracks of China's fossil energy water footprint and electric power water footprint in time and space are depicted, and the spatial matching relationship between China's energy water footprint and water resources is analyzed by combining the center of gravity, standard deviation ellipse model and energy water footprint pressure index. The following conclusions are obtained:

(1) In terms of time, the water footprint of fossil energy increased first and then decreased in the study period with 2012 as the boundary, and the proportion of natural gas water footprint continued to increase, but the proportion was small; the electricity and water footprint continued to grow during the study period, and the proportion of

hydropower continued to increase. The electric water footprint is larger than the fossil energy water footprint, but the electric grey water footprint is smaller than the fossil energy grey water footprint. Under a certain amount of energy production, the increase in the proportion of hydropower in the energy production structure not only makes full use of water resources, but also directly reduces the pollution of energy production to water resources.

(2) From the perspective of spatial pattern, the water footprint of fossil energy generally increases in the west and decreases in the east with the Huhuanyong line as the boundary. The spatial pattern has changed from areas along the Huhuanyong line as the main high-value area in 2004 to on the evolution trend of agglomeration with the Inner Mongolia Shanxi Shaanxi region as the high-value center in 2016; the power and water footprints in all regions are increasing year by year. The power and water footprint dividing line divides Inner Mongolia, Shanxi, Shaanxi, Shandong, Henan and other regions to the north of the boundary into thermal power water footprint concentration areas, and Sichuan, Hubei, Yunnan, Guizhou, Guangxi and other regions to the South of the boundary into hydropower and water footprint concentration areas. The rapid growth of hydropower and water footprint makes the power and water footprint increment in the south of the boundary generally higher than that in the north of the boundary, and gradually forms along the Yangtze River Basin The evolution trend of high-value agglomeration in the Pearl River Basin and the southeast coast.

(3) The spatial matching degree of energy water footprint and available water resources fluctuates and decreases, and the spatial matching degree of fossil energy water footprint is lower than that of electric power water footprint and available water resources. The matching degree between energy and water footprint and available water resources is high in the south and low in the north. In the north, the energy water relationship is tense and restricted, and in the south, the energy water relationship is moderate. The energy water mismatch area accounts for 1/3 of the whole country, mainly distributed in North China and Shaanxi Gansu Ningxia region. North China is not only an area with high pressure of energy water matching, but also a high value area of raw coal water footprint and thermal power water footprint. The energy water contradiction between raw coal production and thermal power generation is the most prominent.

4.2 Discussion

As a whole, China's energy and water footprint is growing, and the mismatch between energy and water footprint and water resources is becoming increasingly prominent, which undoubtedly aggravates the problem of water shortage in China. While reducing the water footprint per unit output in the life cycle of energy production through technological innovation, the spatial pattern of the energy industry should be reasonably adjusted to optimize its water demand allocation. In the 13th five–year plan for energy development, it is proposed that the energy industry should develop according to water resources, develop and adjust the energy industry in areas rich in water resources, and fully consider the regional resource carrying capacity while promoting economic development. This paper holds that the shortage of water resources caused by energy production in the energy–water relationship tense region has affected other local economic activities and residents' lives, and energy production should be reduced to alleviate the pressure on water resources; energy water relationship restricted regions should reasonably adjust the energy industrial structure of such regions, increase the proportion of clean energy with less energy and water footprint per unit output such as natural gas, and make economic development and water resources protection go hand in hand; regions with moderate energy water relationship can reasonably develop energy industry according to local resource endowment, and regions with small fossil energy reserves can appropriately develop new energy such as wind energy, nuclear energy and tidal energy. In addition, the formulation of laws and regulations on energy water related management and the clarification of relevant indicators will also promote the coordinated development of energy and water resources.

The main contributions of this paper are as

follows: firstly, the energy and water footprint is used as an indicator to measure the occupation and pollution of water resources in the life cycle of energy production. Compared with the indicators such as energy and water consumption, the energy and water footprint is closer to the real water consumption, which makes up for the deficiency of the existing domestic multi resource correlation research on the quantitative correlation analysis between energy and water resources; secondly, compared with many single year energy and water footprint studies, multi-year data make up for the lack of research on the evolution trend of energy and water footprint in time and space dimensions; thirdly, in view of the deficiency of the existing research on the relationship between energy and water footprint and water resources matching, the energy and water footprint pressure index is used to measure the pressure caused by energy production on water resources, and then the difference degree of spatial matching between energy and water resources in each region is compared.

This paper is in the stage of basic exploration, and there are inevitably some shortcomings: as China has not yet formulated the standards for unit water consumption and COD emission of some energy, it will bring some deviation to calculate with the results of existing literature; this paper does not consider the deviation of water footprint per unit energy output caused by the use of alternative water sources and recycled water in various regions, the type and degree of fossil energy processing or washing, the nature of mined coal seams and the evaporation rate of stored water; since the relevant data of new energy such as wind energy, nuclear energy and tidal energy cannot be obtained, the impact of its water footprint on the overall energy and water footprint is not calculated in this paper.

Conflict of interest

The authors declared no conflict of interest.

References

1. Chen Q, An T, Lu S, *et al*. The water footprint of coal-fired electricity production and the virtual water flows associated with coal and electricity transportation in China. Energy Procedia 2019; 158: 3519–3527.
2. Ali B, Kumar A. Development of life cycle water footprints for oil sands-based transportation fuel production. Energy 2017; 131: 41–49.
3. Ma X, Yang D, Shen X, *et al*. How much water is required for coal power generation: An analysis of gray and blue water foot−prints. Science of the Total Environment 2018; 636: 547–557.
4. Okadera T, Geng Y, Fujita T, *et al*. Evaluating the water footprint of the energy supply of Liaoning Province, China: A regional input–output analysis approach. Energy Policy 2015; 78(3): 148–157.
5. Zhang C, Anadon LD. Life cycle water use of energy production and its environmental impacts in China. Environmental Science & Technology 2013; 47(24): 14459–14467.
6. Liao X, Zhao X, Jiang Y, *et al*. Water footprint of the energy sector in China's two megalopolises. Ecological Modelling 2019; 391: 9–15.
7. Xiao Z, Yao M, Tang X, *et al*. Identifying critical supply chains: An input–output analysis for Food–Energy Water Nexus in China. Ecological Modelling 2019; 392: 31–37.
8. Okadera T, Chontanawat J, Gheewala SH. Water footprint for energy production and supply in Thailand. Energy 2014; 77: 49–56.
9. Scherer L, Pfister S. Global water footprint assessment of hydropower. Renewable Energy 2016; 99: 711–720.
10. Ghani HU, Silalertruksa T, Gheewala SH. Water–energy–food nexus of bioethanol in Pakistan: A life cycle approach evaluating footprint indicators and energy performance. Science of the Total Environment 2019; 687: 867–876.
11. Ma X, Zhai Y, Zhang R, *et al*. Energy and carbon coupled water footprint analysis for straw pulp paper production. Journal of Cleaner Production 2019; 233: 23–32.
12. Ding N, Liu J, Yang J, *et al*. Water footprints of energy sources in China: Exploring options to improve water efficiency. Journal of Cleaner Production 2018; 174: 1021–1031.
13. ISO. ISO 14046: 2014 environmental management–water, footprint–principles, requirements and guidelines. Switzerland: ISO; 2014.
14. Sun C, Bai T, Wu Y, *et al*. Driving effect of per capita grey water footprint in China from the perspective of factor and efficiency coupling. Journal of Natural Resources 2018; 33(9): 1490–1502.
15. Han Q, Sun C, Zou W. Grey water footprint efficiency measure and its driving pattern analysis on provincial scale in China from 1998 to 2012. Resources Science 2016; 38(6): 1179–1191.
16. Li Y, Guo X, Guo D. An evaluation method of water resources carrying capacity and application. Progress in Geography 2017; 36(3): 342–349.
17. Chen J, Zhang S, Hua D, *et al*. A study on water resources guarantee in Beijing City based on water footprint evaluation. Resources Science 2010; 32(3): 528–534.

18. Bai J, Zhang H. Spatio-temporal variation and driving force of water–energy–food pressure in China. Scientia Geographica Sinica 2018; 38(10): 1653–1660.
19. National Bureau of Statistics of the People's Republic of China. China Energy Statistical Yearbook. Beijing: China Statistics Press; 2005–2017.
20. National Bureau of Statistics of the People's Republic of China. China Statistical Yearbook. Beijing: China Statistics Press; 2005–2017.
21. State Environmental Protection Administration (inventor). Cleaner Production Standard–Coal Mining and Processing Industry. Chinese patent. HJ 4462008. 2008 Nov 21.
22. State Environmental Protection Administration (inventor). Emission Standard for Pollutants from Coal Industry. Chinese patent. GB 20246-2006. 2006 Oct 1.
23. Li H. The study on cleaner production index system for oil & natural gas exploitation (thick oil). Environmental Protection of Oil & Gas Fields 2003; 13(1): 16–18.
24. State Environmental Protection Administration (inventor). Emission Standards for Pollutants in Petroleum Refining Industry. Chinese patent. GB 31570-2015. 2015 Jul 1.
25. National Bureau of Statistics of the People's Republic of China. China Environmental Statistical Yearbook. Beijing: China Statistics Press; 2016.
26. Wang W. Ecological analysis and optimized utilization of water resources in petrochemical industry [PhD thesis]. Shanghai: Tongji University; 2007.
27. Sichuan Academy of Water Conservancy. Water Consumption Quota in Sichuan (Revised Manuscript). Chengdu: Sichuan Academy of Water Conservancy; 2010.
28. State Environmental Protection Administration, General Administration of Quality Supervision, Inspection and Quarantine. Environmental Quality Standards for Surface Water. Chinese patent. GB 3838-2002. 2002 Jun 1.
29. Lei Y, Liu Q, Tang W, *et al*. Promoting role of energy saving and emission reduction of natural gas treating plant on low carbon economy. Chemical Engineering of Oil & Gas 2011; 40(4): 358–361.
30. Liu J, Zhao D, Gerbens-Leenes PW, *et al*. China's rising hydropower demand challenges water sector. Scientific Reports 2015; 5(1): 1–14. DOI: 10.1038/srep11446.
31. Ministry of Industry and Information Technology, Ministry of Water Resources, National Bureau of Statistics of the People's Republic of China, *et al*. The guidance of water efficiency in main industry sectors [Internet]. Available from: http://www.gov.cn/gzdt/att/att/site1/20131022/001e 3741a2cc13d062f701.pdf.
32. Zhu F, Zhong L, Wang Q, *et al*. Huodian hangye zhuyao wuran chanwu paifang xishu (Chinese) [Emission coefficient of main pollution products in thermal power industry]. Beijing: China Statistics Press; 2009.